Using Events in Annulus Regions around Piled-up Sources on ACIS for Spectral and Temporal Analysis

– With an Application to the sources in *Chandra* Orion Ultra-deep Project –

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1. Introduction

The X-ray CCDs realize energy resolution capability by counting the number of electrons produced by photo-electric absorption of an X-ray photon by the device medium and subsequent ionization, where the number of electrons in a detection cell is proportional to the incident X-ray energy. This assumes that no multiple X-ray photons land on a single cell within a readout time frame. If two photons with the energy of E_1 and E_2 land on the same detection cell in the same frame, we have no measure to distinguish it from a single photon with the energy of E_1+E_2. The phenomenon, known as pile-up, causes distortion in the spectrum and the PSFs, grade migrations, and underestimate of event rates.

Davis (2001, ApJ, 562, 575) developed a method for the X-ray spectral analysis of piled-up sources and implemented it in the commonly used fitting software packages. In these implementations, he uses a non-linear modification to the standard integral equation relating the observed pulse height histogram and the source spectrum. This method is effective in analyzing the spectrum of mildly piled-up sources.

Two reasons motivated us to develop another method for pile-up sources during our effort of constructing the X-ray source catalog detected by the 850 ks *Chandra* ACIS-I observation on the Orion Nebula Cluster (ONC). The first is that we have a dozen of heavily piled-up sources at various off-axis angles, which are beyond the scope of the existing pile-up remedy. This, in turn, makes this field one of the best test fields to develop a new method that has a wider scope in pile-up mitigation. The second is that, in addition to the X-ray spectra, we are also interested in light curves of these sources. YSOs, which comprise most of the detected sources in ONC, are not constantly bright sources, but show frequent flares. In this poster, we present a novel method for spectral and temporal analyses of piled-up sources of any degree of pile-up.

2. Methodology

2.1. Overview

The basic idea is to use only the events in the annulus region (r_{in}; the inner radius, r_{out}; the outer radius) in the outskirts of PSFs of piled-up sources. We discard all events in the central core that are spectrally and spatially distorted by pile-up. Because most of the piled-up sources are bright enough, this still leaves us sufficient photons to characterize features of these X-ray sources.

We have to construct an appropriate set of RMF and ARF for the annulus event analysis. For RMF, we can utilize the RMF created at the center of the source, because the spatial dependence of RMFs is negligible in a scale of a PSF size. The ARF, on the other hand, should be tailored for a given annulus region since the effective area (EA) depends on the photon accumulation region and the incident X-ray energy. We developed an IDL code (mkannuarf), in which we calculate the correction factor (CF) between EAs in the ARF files of the annulus region and the whole PSF at each energy bin and create an ARF file for the annulus analysis. Figure 1 shows the diagram of the analysis.

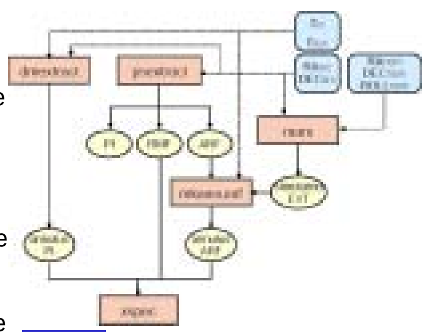
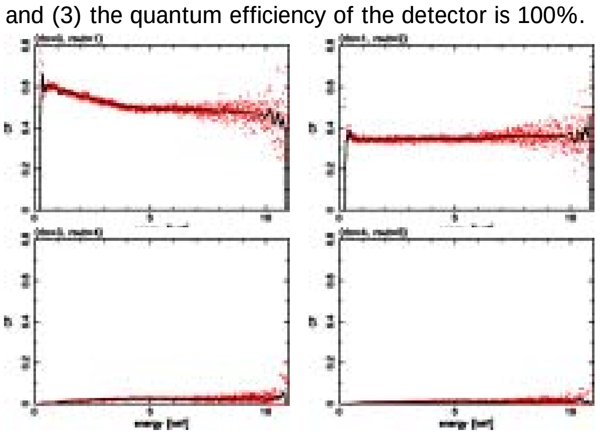


Fig.1 Diagram of the annulus spectral fitting. The input parameters (*ovals*) are given to the tools (*rectangles*) that produce the files (*ellipses*).

2.2 Creating Annulus ARFs

CF is a function of the incident X-ray energy (E), r_{in}, and r_{out} and is expressed as $A_{eff}^{(annu)}(E, r_{in}, r_{out}) = CF(E, r_{in}, r_{out}) \times A_{eff}^{(all)}(E)$, where $A_{eff}^{(annu)}(E, r_{in}, r_{out})$ and $A_{eff}^{(all)}(E)$ are EAs of the annulus and the whole PSF regions. We take a practical approach to determine CF. First, we simulate an event file with a very good statistics (e.g., 10^7 counts) using MARX at the same position on the detector with the source of interest. Second, we count the number of events included in the annuls and the whole PSF regions in the simulated event file. The ratio of events at each energy bin roughly gives the CF if (1) the input spectrum for the MARX simulation is a flat spectrum, (2) the RMF is a unit matrix, and (3) the quantum efficiency of the detector is 100%.



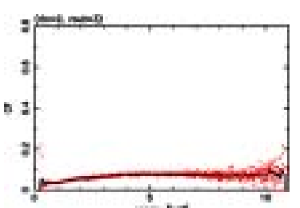


Fig.2 CF of different annulus radii of an on-axis source. The CF (*vertical axis*) is plotted against incident X-ray energy (keV; *horizontal axis*) for the annulus regions of 5 sets of (r_{in}, r_{out}). The unit of radii is pixel.

Fig.2 shows the ratio of counts (*red dots*) of the annulus and the whole PSF regions at each energy bin with various sets of r_{in} and r_{out} of an on-axis source. Since the ratio statistically scatters, we convolve it with a low-pass filter to obtain a smooth CF (*solid curve*). Some scattering still remains beyond ~10 keV, which does not affect the result because the EA values are almost zero at this energy range. Fig.3 illustrates EA against energy for the annulus regions of different radii.

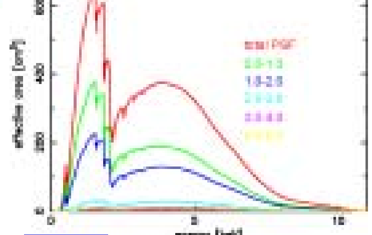


Fig.3 EA vs energy of different photon extraction regions.

2.3 Validating the Method

The spectral fittings using the events and tailor-made ARF in an annulus region should be confirmed that they reproduce the original source spectrum. As the most simple case, we simulated a bright but not piled-up source at on-axis with a flat spectrum (0.03-12.0 keV) with the normalization (N) and the power-law index (Γ) of 8.35x10^{-3} s^{-1} cm^{-2} keV^{-1} and 0, respectively. We took several annulus regions from r =0 to 10 pixel with a bin size of 0.5 pixel to extract events, and fitted the spectra with a power-law model thawing both N and Γ. Fig.4 shows the best-fit parameters as a function of the annulus radius.

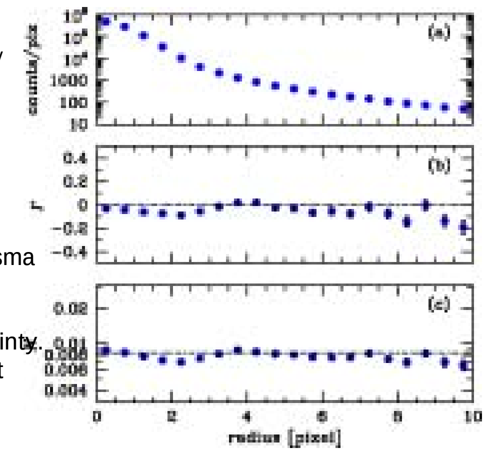


Fig.4 (a) Radial profile of a MARX-simulated unpiled-up on-axis source. (b, c) Best-fit Γ and N of the fitting at each annulus. The dashed-and-dotted lines represent the input parameter value of the simulation.

We next checked that the annulus spectra reproduces the input spectrum in case of more realistic spectral shapes; power-law with Γ =0.5 and 1.0, and thin-thermal plasma (mekal) with k_BT = 0.8 and 2.0 keV. The input parameters were confirmed to be reproduced in any cases within 1σ uncertainty. We also checked that the method does not depend on the off-axis angles.

2.4 Determining r_{in} and r_{out}

The discussion in the previous subsections confirmed that a spectrum extracted from an annulus region reproduces the original source spectrum. We need to determine an appropriate set of annulus radii (particularly r_{in}) to exclude piled-up events.

We simulated a piled-up source at the ACIS-I on-axis position using MARX. The normalization (N) and power-law index (Γ) of the simulation were 8.35x10^{-3} s^{-1} keV^{-1} and 0 (a flat spectrum). Fig.5 (a) shows the radial profile of the simulated source in the unit of surface brightness (s^{-1} pixel^{-1}), where blue circles indicate piled-up profile and red circles indicate the profile if there was no pile-up. We sliced the events along the radius with 0.5 pixel bin to obtain annulus spectra and fit them with the pile-up model implemented in sherpa. The best-fit parameters of the fittings; the pile-up fraction (P.F.), Γ, and N are summarized in Fig.5 (b-d) along the radius. The dashed-and-dotted lines in (c) and (d) show the input parameter.

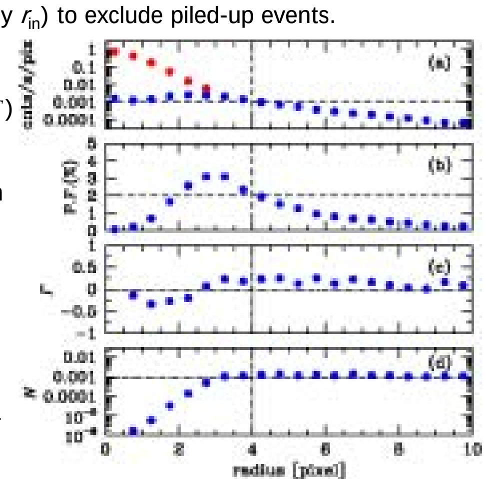


Fig.5 Radial profiles of piled- and unpiled-up sources and the results of annulus fittings.

In the innermost part of the profile (the radius less than ~4 pixel), we see the result is unsatisfactory, where the normalization value is far below the input value and even the pile-up fraction is not derived properly. In the outer part, on the other hand, we see a satisfactory result with the best-fit parameter values of N and Γ consistent with the input value and the pile-up fraction of less than ~2%. The pile-up fraction of 2% corresponds to the surface brightness of ~1.2x10^{-3} s^{-1} pixel^{-1}, which are represented with the dashed lines in Fig.5 (a) and (b).

We use this surface brightness value as the criterion to determine r_{in}; i.e., the first radius value along decreasing radius that attains this surface brightness should be set r_{in} and all the events with $r < r_{in}$ should be discarded from spectral fittings. This is a simple and model-independent quantity that we can calculate for any sources. This can be applied to sources of any brightness by taking a larger annulus radius as the source brightness increases. Moreover, we can use the same criterion for sources at any off-axis angles because, regarding pile-up, the same affect can be expected for the same value of count rate per pixel whatever off-axis angle or whatever distance from the center of the source the pixel is located.

3. Application

We applied our pile-up analysis to the brightest X-ray sources detected in the ~850 ks *Chandra* observation on ONC (see also the oral presentation by E. D. Feigelson and the poster presentation by K. Getman). Among ~1,600 X-ray detections, we picked up 65 sources that satisfies either (1) the total number of counts exceeding or (2) the maximum count rate per pixel in their light curve above 0.003 s^{-1} pixel^{-1}. Fig.6 shows an example of the spectra and light curves of the annulus and the total PSF regions.

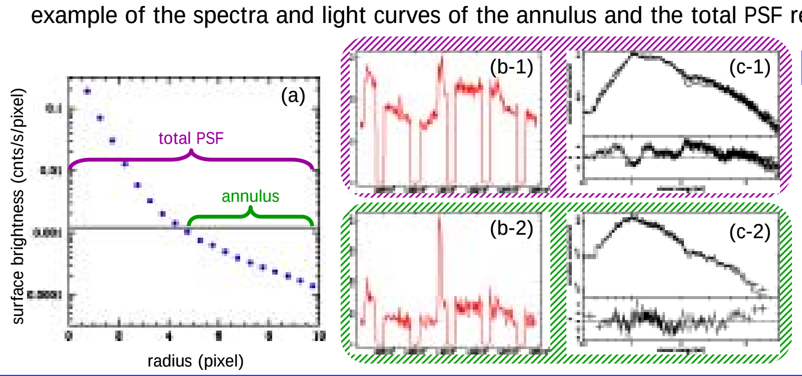


Fig.6 (a) The radial profile of an Orion source, from which the annulus redius is determined. (b-1) and (b-2), and (c-1) and (c-2) are the spectra and light curves of the total PSF and the annulus regions.